Si 34/987

Preprint from the 1987

BUREAU OF MINES MINERALS YEARBOOK

Silicon

UNITED STATES DEPARTMENT OF THE INTERIOR

The statistical data in this volume represents the most comprehensive, verified, domestic and international coverage for 1987 at the time the volume went to press. More recent information can be found in the monthly Silicon Mineral Industry Surveys obtainable from Publications Distribution, Bureau of Mines, Box 18070, Cochrans Mill Road, Pittsburgh, PA 15236.

I 28.37/a:

READEX FICHE best copy available

UNITED STATES DEPARTMENT OF THE INTERIOR • Donald Paul Hodel, Secretary

BUREAU OF MINES • T S Ary, Director

This publication is a chapter from the current Bureau of Mines Minerals Yearbook, comprising *Volume I, Metals and Minerals; Volume II, Area Reports: Domestic; Volume III, Area Reports: International.* The separate volumes of the Yearbook are sold by the Superintendent of Documents, Washington, D.C. 20402.

Silicon

By Clark R. Neuharth[1]

Demand for silicon ferroalloys and silicon metal overall increased compared with that of 1986 owing to increased production of aluminum, iron and steel, and silicon-base chemicals. Domestic producers increased production to meet demand since exports of both ferrosilicon and silicon metal increased and imports of silicon materials overall were only slightly higher than those of 1986.

Domestic Data Coverage.—Domestic production data for the silicon commodity are developed by the Bureau of Mines by means of monthly and annual voluntary domestic surveys. Typical of these surveys is the monthly "Silicon Alloys" survey. Of the 17 canvassed operations to which a survey collection request was made, all responded, representing 100% of the total production shown in table 1.

Table 1.—Production, shipments, and stocks of silvery pig iron, ferrosilicon, and silicon metal in the United States in 1987

(Short tons, gross weight, unless otherwise specified)

Alloy	Silicon content (percent)		Producers' stocks, Dec. 31, 1986[r]	Gross production	Net shipments	Producers' stocks, Dec. 31, 1987
	Range	Typical				
Silvery pig iron	5-24	18	W	W	W	W
Ferrosilicon	25-55	48	57,211	312,220	254,996	40,759
Do	56-95	76	22,730	47,564	51,409	16,801
Silicon metal (excluding semiconductor grades)	96-99	98	5,193	150,080	149,713	4,135
Miscellaneous silicon alloys (excluding silicomanganese)	32-65		15,408	73,525	68,461	16,090

[r]Revised. W Withheld to avoid disclosing company proprietary data.

Legislation and Government Programs.—House bill (H.R.) 3 and its counterpart, Senate bill (S.) 490 entitled "Omnibus Trade Act of 1987," were introduced in the U.S. House of Representatives and Senate. The purpose of S. 490, which was subsequently passed by the Senate and incorporated into H.R. 3, was to revise trade remedy statutes, such as dumping and subsidy laws. H.R. 3 would create sweeping changes in existing trade laws governing import relief and other aspects of international competitiveness. S. 556 and its counterpart, H.R. 1580, were subsequently introduced for the purpose of prohibiting U.S. investment in the Republic of South Africa, as well as exports to and imports from that country. However, these sanction bills included clauses exempting any minerals or materials considered by the President and Congress to be strategic to defense needs. This exemption would very likely include ferroalloys and related ores.

On July 1, the United States removed imports of Brazilian silicon metal from the Generalized System of Preferences exemption list, placing a 5.3% duty on imports of silicon metal in the 99.0% to 99.7% purity category.

A West Virginia law was passed giving a tax break to power companies that supply ferroalloy producers in that State. Under the new law, power companies were not subject to gross sales tax on power distribut-

ed to produce ferroalloys. However, the power companies were required to pass along the savings to the ferroalloy producers through rate reductions.

DOMESTIC PRODUCTION

Production and shipments of silicon-containing ferroalloys and silicon metal overall showed significant increases compared with those of 1986. The standard 50% (25% to 55%) grade and miscellaneous silicon alloy production levels increased over 20%. Magnesium ferrosilicon accounts for the major portion of miscellaneous silicon alloys. Production of silicon metal also increased nearly 20%, although that of 75% (56% to 95%) grade decreased by about one-quarter. Producers' stocks of silicon-containing materials were down overall at yearend owing to high demand from consuming industries.

Applied Industrial Minerals Corp. shut down its Kimball, TN, ferrosilicon plant early in the year owing to competition from low-priced imports. SKW Alloys Inc. started silicon metal production in January after completing the conversion of one of its ferrosilicon furnaces in Niagara Falls, NY. Universal Consolidated Cos. purchased M. A. Hanna Co.'s ferronickel smelter in Riddle, OR, which the company had previously closed. However, Universal planned to reactivate the facility to produce ferrosilicon in 1988.

Moore McCormack Resources Inc. completed the sale of Globe Metallurgical Inc., a silicon and ferrosilicon producer, to a management group backed by Lee Capital Corp., an investment banking firm based in Boston, MA. Globe planned to continue producing silicon metal, magnesium ferrosilicon, and 50% ferrosilicon at its facilities in Beverly, OH, and Selma, AL.

Foote Mineral Co. sold both of its ferrosilicon production facilities at the end of the year. The Graham, WV, plant, which had been closed since 1985, was purchased by an employee group under the name American Alloys Inc. The new company planned to start production of 50% ferrosilicon by March 1988 and possibly convert some of its capacity to silicon metal production later in the year. Keokuk Ferro-Sil Inc., a group formed by former Foote employees, purchased the Keokuk, IA, facility and planned to continue production of silvery pig iron and 50% ferrosilicon.

Nippon Kokan K.K. indefinitely postponed construction of its $60 million polysilicon production facility in Millersburg, OR, owing to sluggishness in U.S. demand for the semiconductor starting material.[2]

Estimated ferrous scrap consumption by the domestic silicon ferroalloys industry to produce silicon ferroalloys was 250,000 tons in 1987, compared with 220,000 tons in 1986.

Table 2.—Producers of silicon alloys and/or silicon metal in the United States in 1987

Producer	Plant location	Product
Aluminum Co. of America, Northwest Alloys Inc	Addy, WA	FeSi and Si.
Applied Industrial Minerals Corp	Bridgeport, AL	FeSi.
Do	Kimball, TN	Do.
Dow Corning Corp	Springfield, OR	Si.
Elkem Metals Co	Alloy, WV	FeSi and Si.
Do	Ashtabula, OH	FeSi.
Do	Marietta, OH	Do.
Foote Mineral Co., Ferroalloys Div	Graham, WV[1]	Do.
Do	Keokuk, IA[2]	FeSi and silvery pig iron.
Globe Metallurgical Inc	Beverly, OH	FeSi and Si.
Do	Selma, AL	Si.
M. A. Hanna Co., Silicon Div	Wenatchee, WA	FeSi and Si.
Ohio Ferro-Alloys Corp	Montgomery, AL	Si.
Reactive Metals & Alloys Corp	West Pittsburgh, PA	FeSi.
Reynolds Metals Co	Sheffield, AL	Si.
SKW Alloys Inc	Calvert City, KY	FeSi.
Do	Niagara Falls, NY	FeSi and Si.

[1]Sold to American Alloys Inc. at yearend.
[2]Sold to Keokuk Ferro-Sil Inc. at yearend.

CONSUMPTION AND USES

Apparent consumption (demand) of silicon-containing ferroalloys and silicon metal increased compared with that of 1986. The overall increase, about 5%, reflected higher production levels in the aluminum, iron and steel, and silicon-base chemical industries. Significant increases were seen in the consumption of standard 50% grade ferrosilicon and miscellaneous silicon alloys that are used in the production of iron and steel. Ferrous applications accounted for about two-thirds of all the silicon materials consumed, based on silicon content. Metallurgical-grade silicon metal produced by tonnage methods is used as the basic raw material in the manufacturing of many chemical products and intermediates such as silicones and silanes. Silanes are used in the production of high-purity silicon for semiconductor devices and solar cells (photovoltaic cells). The Bureau of Mines does not collect data on electronic grades of silicon, which are relatively low in quantity but have a high unit value. The aluminum industry uses silicon metal in the production of wrought and cast products.

PRICES

Prices for silicon-containing ferroalloys and silicon metal were generally higher than those of 1986 owing to tight supplies created by increased demand from the aluminum, iron and steel, and silicon-base chemical industries. The published prices for domestically produced 50% and 75% grade ferrosilicon remained essentially unchanged through the first half of the year, but increased nearly 20% through the second half to 47 cents per pound of contained silicon. The respective average yearly prices of 41.3 and 40.3 cents per pound for 50% and 75% grade ferrosilicon were only slightly higher than those of 1986. The published prices for domestically produced silicon metal remained unchanged throughout the year, ranging from 62.0 to 67.35 cents per pound, depending on iron content.

Posted import prices for 50% and 75% grade ferrosilicon started the year much lower than those of domestically produced material, but both ended the year in line with the domestic list price of 47 cents per pound. The respective average prices for imported 50% and 75% grade ferrosilicon, 37.8 and 36.2 cents per pound, were about 10% higher than those of 1986. The posted price for imported silicon metal also increased steadily during the year to a level of 63 cents per pound, averaging 57.6 cents per pound. The average price was 4% higher than the average for 1986.

FOREIGN TRADE

Exports of ferrosilicon increased 33% in terms of gross weight, although the value of exported ferrosilicon was 40% higher than that of 1986. Over one-half of that material was shipped to Canada. Ferrosilicon was exported to 23 other countries. Silicon metal exports increased 72%, although the value increased 63%. Nearly 70% of the silicon metal exported was shipped to Japan, with the remainder distributed among 33 other countries.

Imports for consumption of ferrosilicon increased slightly compared with those of 1986, and at 230,658 tons was the largest amount ever imported by the United States. Although imports of most ferrosilicon categories increased, imports of 75% grade ferrosilicon (over 60% but not over 80% silicon), which normally account for the largest share of imports, decreased 7%. Imports of silicon metal overall decreased 10%, owing mostly to a significant decrease in shipments from Brazil.

Table 3.—U.S. exports of ferrosilicon and silicon metal

Year	Quantity (short tons)	Value (thousands)
FERROSILICON		
1983	18,338	$10,712
1984	29,364	21,135
1985	12,969	12,671
1986	11,331	8,307
1987	17,049	11,647
SILICON METAL		
1983	2,767	47,826
1984	4,420	88,543
1985	2,120	61,647
1986	5,378	65,157
1987	9,247	166,313

Source: Bureau of the Census.

Table 4.—U.S. imports for consumption of ferrosilicon and silicon metal, by grade and country

Grade and country	1986 Quantity (short tons) Gross weight	1986 Quantity (short tons) Silicon content	1986 Value (thousands)	1987 Quantity (short tons) Gross weight	1987 Quantity (short tons) Silicon content	1987 Value (thousands)
Ferrosilicon:						
Over 8% but not over 30% silicon:						
Brazil	22	6	$17	3,527	575	$1,080
Canada	--	--	--	51	15	9
China	--	--	--	22	6	8
Germany, Federal Republic of	65	11	62	--	--	--
Japan	--	--	--	2	1	2
South Africa, Republic of	--	--	--	73	11	33
United Kingdom	17	3	24	--	--	--
Total[1]	103	19	103	3,673	607	1,132
Over 30% but not over 60% silicon, with over 2% magnesium:						
Brazil	2,638	1,194	1,351	5,677	2,523	2,908
Canada	130	60	26	495	266	145
France	442	202	388	76	36	80
Germany, Federal Republic of	287	150	746	608	331	1,859
Italy	40	18	27	60	27	46
Japan	55	25	97	109	48	202
Mexico	17	8	11	22	10	15
Norway	189	84	135	--	--	--
United Kingdom	--	--	--	18	10	30
Total[1]	3,797	1,741	2,781	6,965	3,252	5,286
Over 30% but not over 60% silicon, not elsewhere classified:						
Argentina	--	--	--	1,683	843	832
Brazil	4,647	2,437	2,507	14,778	7,494	6,894
Canada	15,321	7,303	4,1[illegible]	7,541	3,660	2,304
France	1,792	1,017	1,387	2,379	1,826	1,794
Germany, Federal Republic of	837	461	876	105	59	141
Iceland	5,512	3,029	1,715	--	--	--
Japan	18	8	34	188	92	366
Mexico	11	6	7	--	--	--
Spain	1,115	640	1,012	1,068	615	1,045
U.S.S.R.	15,425	7,338	3,638	31,003	14,887	9,137
Venezuela	5,013	2,406	1,182	--	--	--
Total[1]	49,690	24,644	16,717	58,747	29,076	22,456

See footnote at end of table.

Table 4.—U.S. imports for consumption of ferrosilicon and silicon metal, by grade and country —Continued

Grade and country	1986			1987		
	Quantity (short tons)		Value (thousands)	Quantity (short tons)		Value (thousands)
	Gross weight	Silicon content		Gross weight	Silicon content	
Ferrosilicon —Continued						
Over 60% but not over 80% silicon, with over 3% calcium:						
Argentina	800	181	$308	1,317	820	$1,285
Brazil	7,151	4,438	6,179	8,200	5,226	6,294
Canada	54	34	51	272	286	152
France	1,925	1,194	1,741	1,606	990	1,450
Germany, Federal Republic of	1,069	674	913	150	90	124
Italy	570	382	508	663	406	560
Mexico	5	4	4	--	--	--
Netherlands	19	12	16	19	13	15
Spain	134	83	125	148	90	139
Venezuela	--	--	--	2,766	2,067	1,316
Total[1]	11,227	6,971	9,846	15,191	10,019	11,267
Over 60% but not over 80% silicon, not elsewhere classified:						
Argentina	--	--	--	10,552	8,086	4,897
Belgium-Luxembourg	--	--	--	666	503	311
Brazil	35,203	26,492	15,822	44,289	33,082	20,246
Canada	23,158	17,653	11,424	17,689	13,438	8,846
Chile	882	683	336	--	--	--
China	--	--	--	2,872	2,163	1,294
Dominican Republic	--	--	--	3	2	18
France	3,456	2,626	1,752	242	175	722
Germany, Federal Republic of	633	465	1,318	703	500	1,916
Iceland	8,271	6,331	3,602	7,220	5,367	3,440
Italy	--	--	--	132	87	123
Japan	36	22	67	--	--	--
Norway	42,290	32,157	18,454	33,784	23,793	15,089
Philippines	--	--	--	20	15	11
South Africa, Republic of	5,797	4,298	2,355	817	613	411
Spain	--	--	--	52	39	37
United Kingdom	--	--	--	1,113	835	502
Venezuela	34,030	24,901	13,818	23,584	17,525	9,662
Yugoslavia	2,646	1,992	1,273	2,018	1,550	864
Total[1]	156,822	117,620	70,221	145,956	109,755	68,410
Over 90% but not over 96% silicon:						
Brazil	209	201	151	154	145	135
Canada	--	--	--	2	2	3
Germany, Federal Republic of	56	55	46	--	--	--
Mexico	1,626	1,545	713	--	--	--
Norway	--	--	--	70	67	62
Total[1]	1,892	1,800	910	226	214	200
Total ferrosilicon	228,031	152,795	160,578	230,658	152,923	108,749
Silicon metal:						
Over 96% but not over 99% silicon:						
Argentina	552	NA	445	--	NA	--
Brazil	255	NA	204	--	NA	--
Canada	5,849	NA	5,784	1,901	NA	1,816
France	48	NA	59	32	NA	41
Norway	--	NA	--	451	NA	388
United Kingdom	205	NA	244	278	NA	339
Yugoslavia	1,948	NA	1,610	--	NA	--
Total[1]	8,856	NA	8,397	2,662	NA	2,544
Over 99% but not over 99.7% silicon:						
Argentina	3,192	3,167	3,005	6,235	6,180	5,880
Belgium-Luxembourg	(2)	(2)	(2)	--	--	--
Brazil	12,620	12,526	12,200	4,807	4,765	4,527
Canada	6,012	5,960	6,795	9,836	9,754	10,632
China	--	--	--	1,831	1,319	1,209
France	2,282	2,265	2,321	512	509	510
Germany, Federal Republic of	11	11	17	(2)	(2)	4
Japan	--	--	--	55	55	48
Norway	70	70	60	180	179	208
Portugal	2,756	2,728	2,818	--	--	--

See footnotes at end of table.

Table 4.—U.S. imports for consumption of ferrosilicon and silicon metal, by grade and country —Continued

Grade and country	1986 Quantity (short tons) Gross weight	1986 Quantity (short tons) Silicon content	1986 Value (thousands)	1987 Quantity (short tons) Gross weight	1987 Quantity (short tons) Silicon content	1987 Value (thousands)
Silicon, metal —Continued						
Over 99% but not over 99.7% silicon —Continued						
South Africa, Republic of	1,766	1,751	$1,756	2,738	2,713	$2,469
Spain	349	346	331	--	--	--
Sweden	768	762	714	1,794	1,778	1,830
Switzerland	--	--	--	19	18	21
Yugoslavia	1,436	1,423	1,488	5,941	5,876	5,621
Total[1]	31,263	31,006	31,507	33,448	33,144	32,960
Over 99.7% silicon:						
Belgium-Luxembourg	2	NA	21	3	NA	54
Canada	(2)	NA	1	2	NA	4
China	--	NA	--	2	NA	36
Denmark	2	NA	120	(2)	NA	97
France	1	NA	212	7	NA	1,036
Germany, Federal Republic of	513	NA	19,054	694	NA	27,685
Hong Kong	--	NA	--	(2)	NA	3
Italy	56	NA	3,409	55	NA	7,624
Japan	146	NA	1,865	55	NA	2,168
Korea, Republic of	(2)	NA	14	(2)	NA	6
Malaysia	--	NA	--	(2)	NA	11
Norway	6	NA	12	--	NA	--
Sweden	1	NA	8	(2)	NA	14
Switzerland	5	NA	466	(2)	NA	4
Taiwan	--	NA	--	1	NA	10
U.S.S.R.	(2)	NA	3	(2)	NA	2
United Kingdom	(2)	NA	90	--	NA	--
Total[1]	733	NA	25,276	820	NA	38,754
Total silicon metal[1]	40,851	XX	65,180	36,930	XX	74,298

[r]Revised. NA Not available. XX Not applicable.
[1]Data may not add to totals shown because of individual rounding of converted units.
[2]Less than 1/2 unit.

Source: Bureau of the Census.

WORLD REVIEW

Demand for silicon-containing ferroalloys and silicon metal increased in many countries compared with that of 1986 owing to increased steel and aluminum production. Prices for both ferrosilicon and silicon metal rose steadily as supplies tightened. However, a continuing production shift from traditional suppliers to developing countries helped to keep the overall market in check.

The European Economic Community (EEC) imposed a 6.2% import duty on Yugoslav ferrosilicon and announced that it would make permanent a provisional antidumping duty of $58 per ton against 75% grade ferrosilicon coming into Europe from Brazil. The EEC also imposed a $58 per ton antidumping duty against ferrosilicon from the U.S.S.R. after imports were found to be entering Western Europe at significantly reduced prices.[3] The United States threatened to impose additional duties on silicon-containing materials from Brazil in retaliation to Brazil's strict import regulations on U.S. computer software.[4]

Argentina.—Silarsa S.A., a new company formed by Stein Ferroalloys S.A. and two units of the A. Johnson & Co. Group of the United States, planned a new venture to produce 16,000 tons per year of silicon metal, primarily for sale in the United States. Startup was scheduled for 1988. Electrometalurgica Andina S.A. increased silicon metal production capacity to 11,000 tons per year by activating a new 12,000-kilovolt-ampere (kV•A) furnace at its San Juan facility.[5]

Australia.—The country's first silicon metal smelter, a joint venture between Pioneer Concrete Ltd. and French metals

producer Pechiney, started production in Tasmania. The plant's single 14-megawatt furnace is capable of producing 12,000 tons per year.[6] Agnew Clough Ltd. and the Australian Industry Development Corp. established a trust to build a 25,000-ton-per-year silicon metal production facility in the Wundowie area. Total cost of the project was projected to be $70 million with construction beginning in 1988.[7]

Brazil.—Production of both ferrosilicon (300,000 tons) and silicon metal (44,000 tons) increased 8% compared with that of 1986. Currently the world's fifth largest ferroalloy producer, Brazil continued to capture more of the world market for silicon products as exports of ferrosilicon and silicon metal increased nearly 25%.

Comargo Correa Metais S.A. neared completion on the construction of its new silicon metal production facility. The plant consists of four 18,000-kV•A furnaces with a combined capacity of 35,000 tons per year. Startup of the facility was scheduled for April 1988. The company also planned for a second phase of the project with an equal amount of capacity to be brought on-line in 1990.[8] Bozel Mineracao e Ferroligãs S.A. started a new 15,000-kV•A silicon metal furnace in Minas Gerais, with the capacity to produce 9,000 tons annually.[9]

Several Brazilian companies planned ferrosilicon capacity expansions, including Cia. de Cimento Portland Maringa, which completed construction of a 15,000-kV•A furnace at its ferroalloy plant in São Paulo.[10]

China.—Silicon metal producers in China, after more than doubling their production capacity over the past several years, continued to increase exports and captured nearly one-half of the Japanese market. Exports of silicon metal to Japan were 61,704 tons, a 68% increase over those of 1986. China also significantly increased its exports of silicon metal to the United States and Western Europe. China increased production of ferrosilicon to meet increasing demand from its domestic steel industry while further expanding into world markets. Ferrosilicon shipments to Japan were nearly five times the amount reported in 1986. The Chinese Government considered strict export controls and significant capacity expansions as means of ensuring material for domestic needs.[11]

France.—Pechiney Électrométallurgie considered a plan to switch production at its Dunkirk plant from ferrosilicon to either silicomanganese or charge chrome. The company decided to close its Saint Beron facility owing to high energy and labor costs and the availability of low-cost imports from Brazil and China. A decision on future production at the temporarily closed Laudon plant was pending.[12]

India.—Ferrosilicon production increased 20% during fiscal year 1986-87, despite electric power shortages caused by the country's worst drought in nearly 100 years. One of the country's major ferrosilicon producers, VBC Alloy Co., announced plans to diversify into specialty ferroalloy products.[13]

Japan.—Consuming industries demanded more ferrosilicon and silicon metal than in 1986 owing to increased steel and aluminum production. The Japanese Ferroalloy Association reported that overall production of ferrosilicon dropped more than 25% in 1987 to 87,900 tons. However, a significant increase in imports helped close the demand gap. Japanese silicon metal imports also increased nearly 10% compared with those of 1986.

Norway.—Elkem A/S, the world's largest silicon metal producer, announced that it would temporarily cut production at its Meraker plant from 35,000 to 19,000 tons per year owing to market conditions. Despite the cut, Elkem's share of world silicon metal production was expected to remain above 20%.[14] Tinfos Jernverk A/S announced the permanent closure of its ferrosilicon and silicon metal plant at Notodden. Production at the Notodden plant, which had a combined ferrosilicon-silicon capacity of over 90,000 tons per year, was stopped at the end of 1986.[15]

Portugal.—Cia. Portuguesa de Fornos Electricos S.A.R.L.'s Nelas facility, which was shut down in late 1986, remained closed pending a court decision on the company's future viability. High electrical power costs and totally depleted stocks were stated as Fornos' major obstacles to reactivating the plant.[16]

South Africa, Republic of.—Rand Carbide Ltd. decided to cut ferrosilicon production by 20% owing to an appreciation of the rand on exchange markets. The company said it would concentrate on selling its remaining production locally.[17]

Spain.—Facing high labor and power costs, ferroalloy producers entered rationalization talks with the Government. Industry sources expected the talks to result in production cutbacks and possible plant closures.[18]

U.S.S.R.—Owing to increased demand from its domestic steel industry, the Soviet Union was believed to be planning a 20%

cut in ferrosilicon exports. Exports of Soviet ferrosilicon to the United States and Japan had significantly increased over the past several years.[19]

Venezuela.—C.V.G. Ferrosilicio de Venezuela C.A. (FESILVEN) planned to increase its ferrosilicon production capacity from 65,000 to 95,000 tons by 1988. FESILVEN also began the initial planning of a silicon metal pro[illegible]t.[20]

TECHNOLOGY

Silicon remains the material of choice in the world semiconductor industry owing mostly to its natural ability to form a surface oxide. The insulating properties of this oxide are important to the planar technology involved in device manufacturing. A number of materials are being considered as replacements for silicon in semiconductor devices because of more attractive semiconductive properties. Gallium arsenide devices have proven to be five times faster than those made of silicon and have a significantly higher radiation hardness (i.e., will withstand greater amounts of radiation). However, with its natural oxide-forming ability and other manufacturing advantages, silicon still holds a comfortable lead in device manufacturing. One of the most recent thrusts of research has been attempts to deposit layers of gallium arsenide onto a silicon substrate in order to take advantage of the most desirable properties of both materials.[21]

Advanced ceramic materials, such as silicon carbide and silicon nitride, have a low density and offer unique properties needed for these materials to become replacements for metals in engineering applications. High strength, hardness, and temperature stability make these materials potentially useful for cutting tools, gas turbine engine components, turbocharger rotors, and heat exchangers. Ceramics are also very corrosion resistant, making them attractive for pump and valve applications in which highly corrosive chemicals are present.[22] Although ceramics offer many desirable properties, their usefulness in engineering applications has been restricted because of brittleness. Ceramic materials can also be very costly and difficult to fabricate into usable products. These failings have slowed the development of the once envisioned completely ceramic internal combustion engine. Recent work has been centered on the development of specific components to improve overall engine efficiency[23] and the joining of ceramic and metal parts.[24]

---

[1]Physical scientist, Branch of Ferrous Metals.
[2]American Metal Market. V. 96, No. 18, Jan. 27, 1988, p. 4.
[3]Metal Bulletin (London). No. 7243, Dec. 10, 1987, p. 19.
[4]American Metal Market. V. 95, No. 232, Dec. 1, 1987, p. 1.
[5]———. V. 95, No. 155, Aug. 11, 1987, p. 1.
[6]Metal Bulletin (London). No. 7242, Dec. 7, 1987, p. 17.
[7]———. No. 7155, Jan. 27, 1987, p. 11.
[8]———. No. 7236, Nov. 16, 1987, p. 13.
[9]The Tex Report. V. 19, No. 4457, June 12, 1987, p. 7.
[10]———. V. 19, No. 4563, Nov. 13, 1987, p. 11.
[11]———. V. 19, No. 4582, Dec. 11, 1987, p. 10.
[12]Page 19 of work cited in footnote 6.
[13]Metal Bulletin Monthly (London). No. 203, Nov. 1987, p. 11.
[14]Metal Bulletin (London). No. 7224, Oct. 5, 1987, p. 9.
[15]The Tex Report. V. 19, No. 4392, Mar. 10, 1987, p. 4.
[16]Metal Bulletin (London). No. 7247, Dec. 24, 1987, p. 11.
[17]The Tex Report. V. 19, No. 4411, Apr. 6, 1987, p. 2.
[18]Metal Bulletin (London). No. 7227, Oct. 15, 1987, p. 17.
[19]———. No. 7244, Dec. 14, 1987, p. 13.
[20]———. No. 7159, Feb. 10, 1987, p. 11.
[21]Materials Edge. No. 2, Nov. 1987, pp. 43-50.
[22]ASTM Standardization News. Oct. 1987, p. 50.
[23]Science News. V. 132, Oct. 3, 1987, p. 214.
[24]Ceramic Bulletin. V. 66, No. 2, 1987, p. 320.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1988—242-377/80034